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# A review of factors affecting environmental and economic life-cycle performance for electrically-driven heat pumps

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## Glossary

|             |  |
|-------------|--|
| <b>GHG</b>  | Greenhouse Gas                                   |
| <b>ZEB</b>  | Zero Energy Building                             |
| <b>LCC</b>  | Life-Cycle Cost                                  |
| <b>LCA</b>  | Life-Cycle Assessment                            |
| <b>HP</b>   | Heat Pump  |
| <b>PV</b>   | Photovoltaic Panel                               |
| <b>PV/T</b> | Photovoltaic/Solar Thermal Installation          |
| <b>GWHP</b> | Ground-Water Heat Pump                           |
| <b>GCHP</b> | Ground-Coupled Heat Pump                         |
| <b>GHP</b>  | Geothermal Heat Pump                             |
| <b>ASHP</b> | Air-Source Heat Pump                             |
| <b>SWHP</b> | Surface Water Heat Pump                          |
| <b>AC</b>   | Air-to-Air Split Conditioning Unit               |
| <b>RAD</b>  | Radiator   |
| <b>RFC</b>  | Radiant Floor Conditioning                       |
| <b>ADV</b>  | Air Ducts and Vents                              |
| <b>GHEX</b> | Ground Heat Exchanger                            |
| <b>BHEX</b> | Borehole Heat Exchanger                          |
| <b>NPV</b>  | Net Present Value                                |
| <b>FC</b>   | Fluid Cooler (i.e. closed-circuit cooling tower) |
| <b>DHW</b>  | Domestic Hot Water                               |
| <b>DH</b>   | District Heating                                 |

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# 1. Introduction

Residential and commercial buildings account for roughly 40 % of the total primary energy consumption in the European Union (EU) [1] and in the world [2]. The integration of renewable energies into buildings and the energy-efficient design and operation of edifices and dwellings can therefore contribute to cut a large share of greenhouse gas (GHG) emissions and to reduce the use of fossil fuels. This important fact has been increasingly recognized at European level: in the recent recast of the Energy Performance of Buildings Directive (EPBD) it is formulated that all new buildings should be “nearly zero energy buildings (nZEBs)” by the end of 2020 [1].

Space heating and cooling together with sanitary hot water supply have a significant share, approximately 50 %, of the global energy consumption of buildings [3]. In order to fulfil energy and energy-efficiency building requirements, European and national legislations encourage the use of more sustainable heating and cooling options. Heat pump (HP) systems are able to use renewable low-enthalpy energy from ambient sources/sinks (such as air, water and ground) for providing space heating and cooling and also water heating, thus being particularly attractive. In the EU, the Renewable Energy Sources (RES) Directive has recognized this favourable fact by identifying the ambient energy from air, water and ground as renewable. The RES Directive also states that renewable energy produced by the HP has to be calculated based on final energy [4]; this has the positive effect of increasing the impact of the RES contribution from HPs in the EU energy mix.

Recent studies [5] [6] [7] [8] [9] [10] [11] [12] adopt life-cycle approaches and tools in the attempt to find the most sustainable heating and cooling solution under different locations and system-design conditions. A sustainable dimension implies that both environmental and economic aspects are taken into account; the life-cycle comparisons of different heating and cooling systems (including HP systems) are therefore based on GHG emissions and costs.

This work focuses only on the economic side of the life-cycle analyses (therefore excluding the environmental dimension) and presents a review of life-cycle cost (LCC) studies involving HP systems. Three first objectives of this review are:

- to present an overview of the main factors characterizing life-cycle cost methodologies for HP systems;
- to understand which factors are the most influential in achieving reliable evaluations;
- to suggest methodological improvements to be employed in order to make LCC analyses more robust.

This is important in order to encourage and facilitate the adoption of LCC studies in the heating and cooling sector and, in particular, when considering solutions including HP systems.

The review of the LCC studies revealed that economic life-cycle performance of HPs depends on a number of different factors such as climatic conditions, operation modes, system-design and economic aspects (e.g. electricity and fuel tariffs). For HP systems

economic performance is closely related to the environmental one since a low efficiency of the HP affects negatively both the operating costs and the GHG emissions. Therefore, even though life-cycle assessment (LCA) studies are not reviewed in this work, factors affecting environmental performance are studied. A fourth objective of this review is to present an overview of factors influencing both the economic and the environmental success of HP systems. A greater awareness and understanding of these factors can, at a macro-level, increase confidence in HP systems so that governments can identify appropriate actions and develop legislation that provide support for HPs implementation.

This review focuses on electrically-driven HPs (based on the vapour-compression refrigeration cycle) since they represent the larger segment of the HP-market. A classification and a general overview of this type of HPs are initially provided. Thermally-driven HPs (i.e. absorption and adsorption HPs) and gas engine-driven HPs are not considered in this study. However, there are currently significant R&D activities going on for these systems and they represent a promising (although small) share of the HP-market [6].

Furthermore, the analysis is limited to residential and commercial applications of HP systems. As a consequence, studies involving industrial or high-temperature HPs have been excluded even though there are already a number of successful examples and the sector is expected to grow [7].

The above-mentioned topics are developed in the following three main sections:

- first, an extensive classification for HP systems is presented together with different possible nomenclatures;
- secondly, an overview of LCC-studies is given describing the most important methodology steps necessary for an accurate life-cycle economic analysis of HPs;
- thirdly and finally, a summary of the main aspects defining the economic and environmental success of HP systems is provided.

Reduction of primary energy consumption and GHG emissions are currently two main drivers for encouraging the adoption of HPs. However, HP systems correctly coupled with energy storage systems and implemented in the buildings with effective controls, can also improve load management and grid balancing in the prospect of an increased future renewable power production. HPs can thus have a beneficial effect on the entire energy system and contribute to realize the smart grid of the future. This favourable fact can further boost the implementation of HP systems in the buildings sector.

## 2. Classification and general overview for electrically-driven heat pumps

HP systems can be classified in many different ways and therefore the possible nomenclatures also vary; common classifications are based on:

- nature of the heat source/sink exploited;
- type of distribution system adopted;
- kind of thermal demand covered.

In Figure 1 a diagram showing a classification for HP systems is presented together with different possible nomenclatures (including the ASHRAE nomenclature [8]). The diagram is further explained in Sections 2.1 - **Error! Reference source not found.** In Section 2.1 a description of the different heat sources/sinks and of the various distribution systems is provided. In Sections 2.2, 2.3, **Error! Reference source not found.** and **Error! reference source not found.** a general overview and an explanation of possible configurations for water- and ground- source HPs are given.

An additional classification, which is not included in the diagram, would take into account the different types of thermal demand covered by the HP. Heating-only and cooling-only HPs exist in the market, but HPs can also be used in a reversible way for both space-heating and space-cooling, eventually implementing free-cooling. In free-cooling mode the environmental heat sink is directly used via a heat-exchanger without the need of a HP. There is also the possibility to use the HP for sanitary hot water (SHW) production in new build or renovation applications as replacement or alternative to electric water heaters. Sanitary hot water heat pumps represent, at the moment, a growing market [7]. These areas are outside scope of this report, so they are not treated further here.

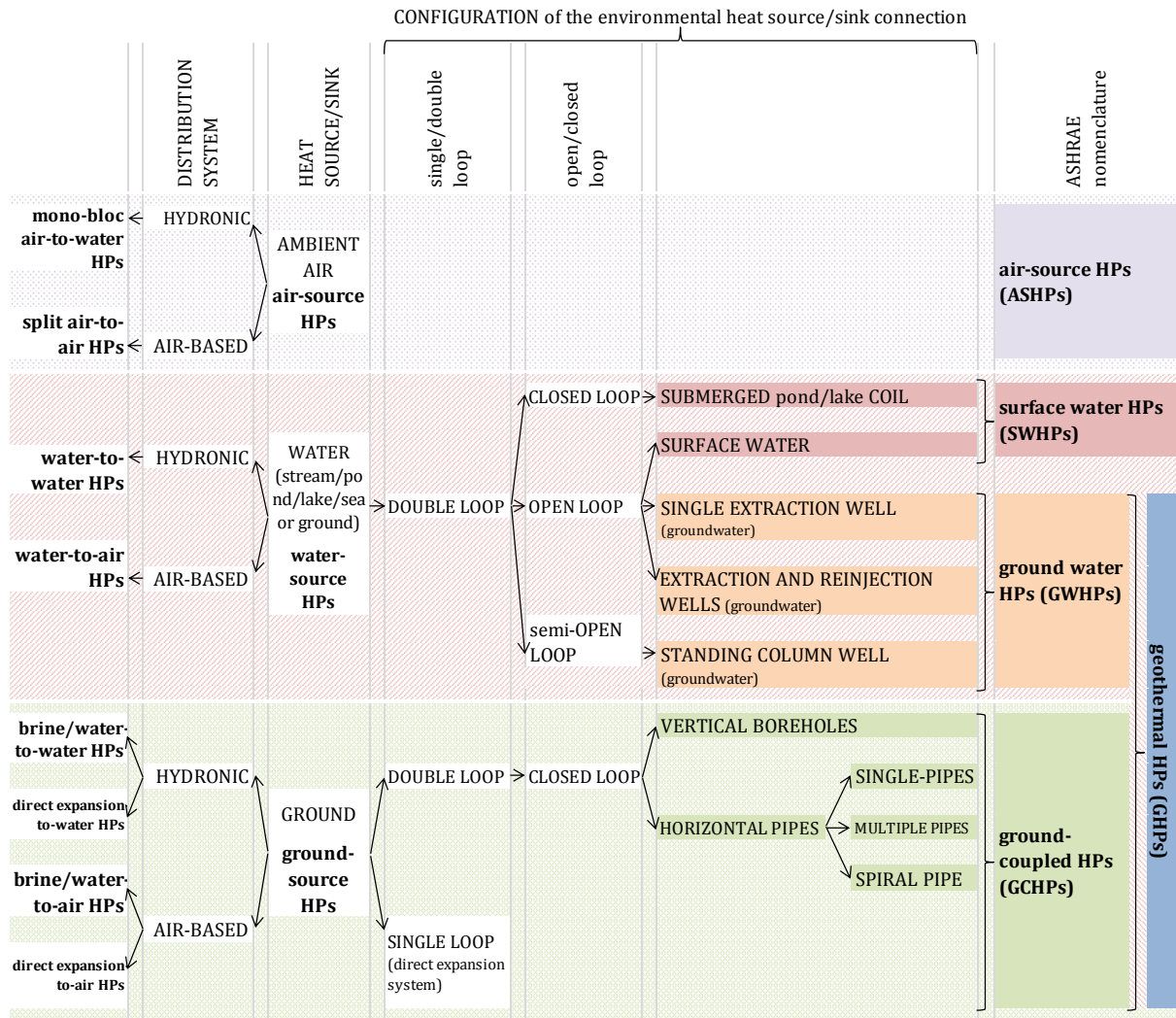


Figure 1 Classification and three nomenclatures (in bold) for HP systems.

## 2.1 Distribution system and heat source/sink

By means of compression and expansion of a refrigerant, a HP transfers heat from a low temperature (i.e. the heat source-temperature) to a higher temperature to be used for space or water heating (see Figure 2); vice versa, in the case of cooling loads, heat is rejected from a low to a higher temperature (i.e. the heat sink-temperature). HPs performance is therefore directly affected by the nature of the heat source/sink; air-, water- and ground- source HPs exist. Water-source HPs can be further differentiated in stream-/pond-/lake-/sea- or ground water- HPs. Moreover there are HPs that use waste heat as heat source. Waste heat HPs can use either industrial waste heat (e.g. hot gases from industrial processes, discharged hot water) or residential waste heat (e.g. warm air from process of ventilation in the case of exhaust-air HPs, heat from sewage treatment); waste heat HPs are not included in the classification of Figure 1.

Temperatures of the water are more constant than in the ground and air, whereas temperature levels of the ground are less fluctuating than for air; therefore water and ground configurations give, in general, higher operating performance compared to air. However, nowadays, variable refrigerant flow (VRF) air-source HPs (ASHPs) can also offer competitive performance in mild climates [3].



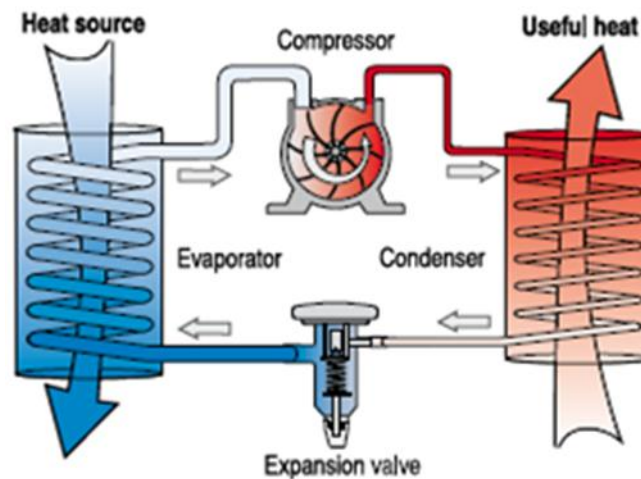


Figure 2 Typical compression/expansion cycle [Source: IEA/Heat Pump Centre]

Currently, air represents the main heat source for HPs sold in the European markets (more than 85 % of the total sales) [7]. This is due to competitive initial investments costs and to the fact that ASHPs consist, mainly, of factory-built units which are easy to install.

Regarding the distribution system, there are air based systems and hydronic ones. Air based systems use air as heat transport medium throughout the building, while hydronic systems use water as heat carrier. Among the hydronic systems there are many different solutions available such as high temperature radiators or localized fan convectors/coils; in the case of HP systems, lower temperature options are particularly important such as floor, wall or ceiling heating [9]. ASHPs can be distinguished in mono-bloc and split units. In the first type the refrigerant with its cycle is contained in a mono-bloc and a separate water distribution system is necessary. In the second type the refrigeration cycle is physically split between indoor and outdoor units and the refrigerant is the heating and cooling medium throughout the building.

## 2.2 Single loop configuration

In the case of water- and ground- source HPs different configurations of the environmental heat source/sink connection are possible; firstly it can be distinguished between double and single loop configurations. In the single loop configuration (also known as direct exchange or direct expansion system) refrigerant is directly circulated from the HP to the ground and, since the HP-evaporator is extended into the ground, there is no need of primary heat exchanger. The ground circulation pump is therefore avoided and the temperature of the refrigerant is very close to the ground one; this affects positively the efficiency of the system [9]. However, the single loop configuration is recommended only for small units (residential and small commercial applications) due to a more difficult installation of the system, a higher refrigerant charge and an increased probability of rupture (tubing damages with consequent refrigerant leaks) compared to a double loop configuration [10] [11].

### **2.3 Double loop configuration**

In the double loop configuration, which is the most common one, a second loop is always present. This second loop is coupled to the HP-refrigerant loop through the primary heat exchanger. The double-loop system can further be classified as closed or open loop system. A third new option is represented by the semi-open loop arrangement (called standing column well heat exchange system) in which the water is returned back into the original extraction well and is heated in its way down by the surrounding rocks. In suitable ground conditions (fractured rocks formations) this system can give a good efficiency [9].

In the closed-loop system, an antifreeze solution is circulated inside a closed coil and exchanges heat with the heat source/sink through the ground heat exchanger; instead, in the open-loop system water is directly pumped from the water source (ground, stream, pond, lake or sea) to the HP and then returned back at a certain distance. In the open-loop configuration there is therefore no need of ground heat exchanger; the water is directly used as energy carrier. In the case of groundwater source, there can be two wells (extraction and reinjection at an adequate distance) or only one extraction well, in this case the water is released into a nearby stream/river/lake/pond/ditch or into a ground drainage field, also known as open drainage; the last one is the easiest and least expensive method [11]. The general problems associated with an open groundwater configuration are: - limited availability of groundwater and possible restrictions on groundwater use; - higher maintenance costs due to fouling, corrosion and clogging in the source-wells and in the primary heat exchanger; - restricted authorizations; - possible higher requirements for pumping. Advantages compared to closed loops are: - simpler design - lower initial costs than for vertical closed loops (as a consequence of lower drilling requirements); - higher thermodynamic performance due to less fluctuating temperatures; - smaller land-area needed [11].

In the case of ground-source HPs, double closed loops can be divided into horizontal or vertical loops according to the positioning of the pipes in the ground.

Horizontal loops consist of pipes laid in trenches about 1-2 m under the soil surface [12]; single-pipe, multiple-pipe and spiral configurations can be distinguished [10]. Multiple-pipe types consist of several straight pipes placed in a single trench, while in spiral configurations pipes are laid out in a circular way inside the trenches.

Vertical loops typically consist of two to three U-shaped plastic pipes which are inserted into deep boreholes. After insertion of the pipes, the boreholes are entirely filled with grout in order to enhance heat transfer and protect groundwater aquifers. Boreholes are usually 50 – 150 m deep [13].

The general advantages of vertical systems compared to horizontal ones are: - smaller installation area required and reduced landscape disturbance (since drilling impacts less than trenching); - shorter pipe length required; - better HP-performance thanks to a more constant temperature over the year [9]. A disadvantage of vertical loops is the increased installation cost since drilling is more expensive than trenching [14] [15].

In the case of water-source HPs the double closed loop configuration consists in coils submerged in a water body (pond/lake or reservoir). These loops are normally anchored at least 1.8 m below the water surface (often at the bottom of the water body) and have the advantage of less pipe length and piping requirement compared to other closed loop systems. Furthermore neither drilling nor trenching are needed, which makes them more

cost-effective compared to other closed loops [9] [11]. However, if the pipes are not installed at an adequate depth, water temperatures can be affected by weather conditions and this affects negatively the performance of the HP systems. Furthermore the availability of usable water bodies close to the users is often limited. These are the main disadvantages of these systems.

The double open loop systems are surface water systems in which the water is extracted directly from the stream, pond, lake or sea and rejected at an adequate distance.

### 3. Life-cycle cost methodologies for heat pumps

Current public and private decisions are frequently based mainly on short-term investment figures; this approach discourages the adoption of more sustainable heating and cooling solutions since potential economic savings due to lower operating and maintenance costs are not taken into account. A life-cycle cost analysis is therefore important in order to evaluate in a long-term perspective the most economical heating and cooling system. This fact has also been recognized by the EPBD recast [1] which states that Member States are encouraged to "assure that minimum energy performance requirements for buildings or building units are set with a view to achieving cost-optimal levels".

In this work LCC studies dealing with HPs are reviewed. The studies cover the period from 1986 till 2014. The heating and cooling systems compared in each analysis are listed in Table 2; characteristics (heated floor area and location) of the buildings where the heating and cooling systems are installed are presented in Table 1.

*Table 1 Characteristics (heated floor area and location) of the buildings in which the heating/cooling systems are installed. A dash means that the information is not available.*

|                             | building heated<br>floor area [m2] | building location                     | ref. |
|-----------------------------|------------------------------------|---------------------------------------|------|
| Robert & Gosselin,<br>2014  | -                                  | -                                     | [11] |
| Alavy et al., 2013          | -                                  | -                                     | [24] |
| Aste et al., 2013           | 1050                               | IT (Milan, Rome,<br>Palermo)          | [5]  |
| Ristimäki et al., 2013      | 21546                              | FI                                    | [10] |
| Self et al., 2013           | -                                  | CA (Alberta, Ontario,<br>Nova Scotia) | [9]  |
| Kegel et al., 2012          | 210                                | CA (Toronto)                          | [21] |
| Rehfeldt, 2012              | -                                  | USA (Alaska)                          | [22] |
| Hackel & Pertzborn,<br>2011 | 19050 \ 23320 \<br>5310            | USA                                   | [23] |
| Dickinson et al., 2009      | 13582                              | UK                                    | [24] |
| Rehfeldt, 2008              | -                                  | USA (Alaska)                          | [25] |
| Chiasson, 2006              | 4386                               | USA                                   | [25] |
| Bernier et al., 2006        | 1486                               | USA (Atlanta)                         | [14] |
| Healy and Ugursal,<br>1997  | 213                                | CA                                    | [12] |
| Kaygusuz, 1993              | 75                                 | TR                                    | [27] |
| Tassou et al., 1986         | 235                                | UK                                    | [28] |

In the reviewed studies the resulting indicator of each life-cycle cost evaluation is the Net Present Value (NPV) which is the sum of the present worth (with reference to the starting year) of all the life-cycle costs including investment costs. This means that all the costs are brought to the initial time by using economic factors i.e. interest and inflation rates. NPV (EUR or EUR/m2) is the parameter allowing the comparison of the different heating and cooling options.

According to the standard EN 15459 [14], in the case of different money fluxes in different years, NPV can be evaluated as:

$$NPV = C_I + \sum_{n=1}^p \frac{C_{O\&M_n}}{(1 + R_R)^n}$$

where  $C_I$  is the INITIAL CAPITAL COST,  $C_{O\&M}$  are the ANNUAL OPERATING COSTS which include: - energy costs, - operation, maintenance and repair costs, - replacement costs,  $p$  is the LIFETIME OF THE PROJECT and  $R_R$  is the REAL INTEREST RATE which is defined as:

$$R_R = \frac{R - R_I}{1 + R_I}$$

where  $R$  is the MARKET INTEREST RATE and  $R_I$  is the INFLATION RATE (annual depreciation of the currency).

The DISCOUNT RATE  $R_D$  is defined as:

$$R_D = \left( \frac{1}{1 + R_R} \right)^y$$

where  $y$  is the year of the considered costs.

Table 2 Overview of the different heating/cooling systems compared in each LCC study.

|                                      | reference conventional<br>systems (base case)  | HP-types  |   |  |  |
|--------------------------------------|--|---|---|--|--|
| Robert & Gosselin, 2014 <sup>a</sup> |  | GCHP <sub>rev</sub> +<br>AUX  |   |  |  |
| Alavy et al., 2013 <sup>b</sup>      |  | GCHP <sub>rev</sub> +<br>AUX  |   |  |  |
| Aste et al., 2013                    | natural gas fired -<br>condensing boiler with<br>RFC + AC                              | ASHP <sub>rev</sub><br>with ADV<br>(air-to-air<br>hp)               | ASHP <sub>rev</sub><br>with RFC<br>(air-to-<br>water hp)                            | GCHP <sub>rev</sub><br>with RFC<br>(brine-to-<br>water hp)               | GWHP <sub>rev</sub><br>with RFC<br>(water-to-<br>water hp) |
| Ristimäki et al., 2013               | DH   | GCHP + PV   | GCHP  |  |  |
| Self et al., 2013                    | electric baseboard<br>heaters natural gas<br>fired furnace<br>with ADV                 | ASHP <sub>h</sub><br>with ADV<br>(air-to-air<br>hp)                 | GHP <sub>h</sub> with<br>ADV<br>(water/bri-<br>ne-to-air<br>hp)                     |  |  |
| Kegel et al., 2012                   | natural gas fired<br>furnace with ADV + AC   | GCHP <sub>rev</sub><br>with ADV<br>(brine-to-<br>air hp)            | ASHP <sub>rev</sub> -<br>high ef.<br>with ADV<br>(air-to-air<br>hp) + AUX           | ASHP <sub>rev</sub> -<br>low ef.<br>with ADV<br>(air-to-air<br>hp) + AUX |  |
| Rehfeldt, 2012                       | 2 oil fired boilers + 1<br>electric boiler with RFC                                    | 3 ASHP <sub>rev</sub><br>+ AUX (el.<br>boiler)                      | GCHP <sub>rev</sub><br>with RFC<br>(water-to-<br>water<br>hp) + AUX<br>(el. boiler) |  |  |
| Hackel & Pertzborn, 2011             | natural gas fired<br>burner  | GCHP <sub>rev</sub> +<br>AUX.                                       | GCHP <sub>rev</sub>   |  |  |
| Dickinson et al., 2009               | natural gas fired boiler<br>+ AC   | GCHP <sub>rev</sub> +<br>AUX.                                       | GCHP <sub>rev</sub>   |  |  |
| Rehfeldt, 2008                       | oil fired boiler with<br>RFC   | GCHP <sub>rev</sub><br>with RFC<br>(water-to-<br>water<br>hp) + AUX |   |  |  |
| Chiasson, 2006                       | propane furnaces with<br>a mix of split systems<br>and rooftop units + AC              | GWHP <sub>rev</sub><br>(open<br>loop)                               |   |  |  |
| Bernier et al., 2006                 |  | GCHP <sub>rev</sub> -<br>high ef. +<br>AUX (fluid<br>cooler)        | GCHP <sub>rev</sub> -<br>high ef.   | GCHP <sub>rev</sub> -<br>low ef.   |  |
| Healy and Ugursal, 1997              | oil fired furnace<br>with ADV<br>+ AC electric baseboard<br>heater<br>with ADV<br>+ AC | ASHP <sub>rev</sub><br>with ADV<br>(air-to-air<br>hp)               | GCHP <sub>rev</sub><br>with ADV<br>(brine-to-<br>air hp)                            |  |  |
| Kaygusuz, 1993                       | coal fired boiler oil fired<br>boiler natural gas fired<br>boiler electric heaters     | ASHP <sub>h</sub><br>with ADV<br>(air-to-air<br>hp)                 |   |  |  |
| Tassou et al., 1986                  | oil fired boiler natural gas<br>fired boiler electric heater<br>electric boiler        | ASHP <sub>h</sub><br>with RAD<br>(air-to-<br>water hp)              |   |  |  |

<sup>a</sup> Life-cycle cost minimization by optimising: - number of boreholes; - length and spacing of boreholes; - size of the HP.

<sup>b</sup> Life-cycle cost minimization by optimising the size of the HP within a hybrid system.

reversible (rev), only-heating (h), ground-coupled heat pump (GCHP), auxiliary conventional system (AUX), ground-water heat pump (GWHP), radiant floor conditioning (RFC), air-source heat pump (ASHP), air ducts and vents (ADV), air-to-air split conditioning unit (AC), geothermal heat pump (GHP), photovoltaic panel (PV), radiators (RAD)

According to Flanagan [15] and Kirk & Dell'Isola [16] (who developed the fundamentals of the LCC theory) there are four main steps to be faced when undertaking a LCC assessment; these four steps can be summarized as it follows:

- STEP I. identifying and technically specifying the different solutions to be assessed;
- STEP II. specifying the main economic parameters to be used (e.g. escalation rates, discount rates, project lifetime, etc.);
- STEP III. determining the cost components and when they occur;
- STEP IV. performing a sensitivity analysis.

Looking at the four steps to be undertaken, the reviewed LCC studies have adopted different approaches which affect the results of the LCC calculations.

Some results of LCC comparisons are reported in Figure 3 for some selected studies ([5], [12], [7], [6], [25]) for which the energy price ratio was easy to identify. The energy price ratio is the ratio between the price of electricity and the price of 1 kWh of useful heating energy delivered by a fossil fuel-driven technology (in this case by a natural gas-fired boiler or furnace). The energy price ratio is reported in the horizontal axis of the chart of Figure 3, while in the vertical axis the percentage of NPV savings  $NPV_{savings}(\%)$  associated with the use of HPs compared to the use of natural gas boilers/furnaces is showed.

The percentage of NPV savings is calculated as:

$$NPV_{savings}(\%) = \frac{NPV_{natural\ gas\ boiler/furnace} - NPV_{HP}}{NPV_{natural\ gas\ boiler/furnace}} \times 100$$

If the savings are negative it means the HP is not economical compared to the conventional option.

In Figure 3 it can be noticed that, even for similar energy price ratios, the outcomes are very different when considering different studies. This is due to the influence of many different location and design factors which affect the performance of the HP systems, but it is partially also due to the fact that different works adopt different LCC approaches which inevitably influence the results. In

Table 3 the focus is on some specific aspects and factors which need to be properly addressed when calculating the NPVs of HP systems; these aspects are highlighted for each of the four above-mentioned steps (STEP I, II, III and IV) and are further developed in the next sections.

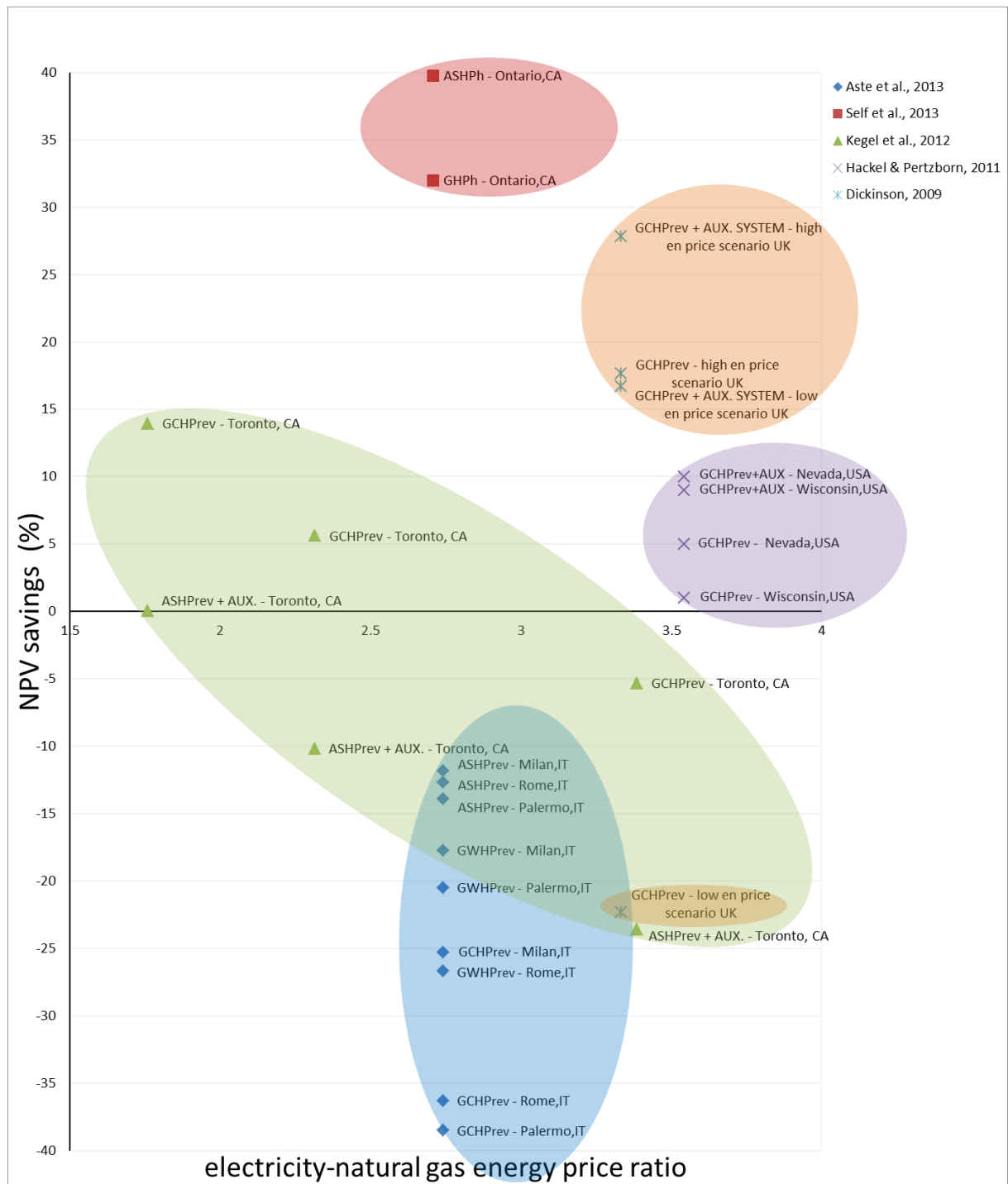


Figure 3 Percentage of NPV savings associated with the use of HPs compared to the use of natural gas boilers/furnaces as function of the energy price ratio.



Table 3 Specific aspects characterizing each LCC study. An empty space means that the information is not available. A tick indicates that the aspect is included in the LCC-analysis, while a cross indicates that is excluded.

|          | Robert & Gosselin, 2014                               | Alavy et al., 2013 | Aste et al., 2013 | Ristimäki et al., 2013 | Self et al., 2013 | Kegel et al., 2012 | Hackel & Pertzborn, 2011 | Rehfeldt, 2012 | Dickinson et al., 2009 | Rehfeldt, 2008 | Chiasson, 2006   | Bernier et al., 2006 | Healy & Ugursal, 1997 | Kaygusuz, 1993 | Tassou et al., 1986 |
|----------|---|--------------------|-------------------|------------------------|-------------------|--------------------|--------------------------|----------------|------------------------|----------------|------------------|----------------------|-----------------------|----------------|---------------------|
| STEP I   | simulation of HP-efficiency                           | ✓                  | X                 | ✓                      |                   | X                  | ✓                        | X              | ✓                      |                | X                | ✓                    | X                     | ✓              |                     |
|          | GHEX simulation                                       | ✓                  | X                 | ✓                      |                   | X                  | ✓                        |                | ✓                      |                | X                |                      | X                     |                |                     |
|          | dynamic energy simulation of building                 | X                  | ✓                 | ✓                      | ✓                 | X                  | ✓                        | ✓              | ✓                      |                | ✓                | ✓                    | X                     |                |                     |
|          | dynamic analysis time-step                            |                    | 1 hour            | 15 min                 |                   | 5 min              |                          |                | 1 hour                 |                |                  | 1 hour               |                       |                |                     |
| STEP II  | electricity-natural gas energy price ratio            |                    |                   | 2.7                    |                   | 2.7                | 3.4 1.8 2.3              | 3.5            | 0.7 <sup>a</sup>       | 3.3            | 0.7 <sup>a</sup> | 0.8 <sup>b</sup>     |                       | 3.8            |                     |
|          | rate of annual increase of electricity cost [%]       |                    | 4                 | 1.5 - 2.5              | 2                 |                    | 0.4                      |                | 1.8                    | 5 - 7.5        | 1.8              | 2                    | 3                     | constan<br>t   | 12 3                |
|          | rate of annual increase of natural gas cost [%]       |                    | 4                 | 3 - 5                  |                   |                    | 1.4                      |                | 6.3 <sup>a</sup>       | 10 - 15.       | 6.3 <sup>a</sup> | 2 <sup>b</sup>       |                       | 12             | 3                   |
|          | real interest rate [%]                                | 6                  | 8                 | 6                      | 2.6               |                    | 6                        | 10             | 2.4                    | 3.5            | 2.4              | 8                    | 7                     | constan<br>t   | 7 5                 |
|          | expected project lifetime [y]                         | 20                 | 20                | 15                     | 25 50 100         | 20                 | 20                       | 20             | 25                     | 20             | 25               | 50                   | 20                    | 15             | 15 20               |
| STEP III | capital cost components                               |                    |                   |                        |                   |                    |                          |                |                        |                |                  |                      |                       |                |                     |
|          | heat source/sink system (e.g. BHEX)                   | ✓                  | ✓                 |                        | ✓                 |                    | ✓                        | ✓              | ✓                      | ✓              | ✓                | ✓                    | ✓                     |                |                     |
|          | installation/civil labour (e.g. drilling, excavation) | ✓                  |                   |                        | ✓                 |                    | ✓                        | ✓              | ✓                      | ✓              | ✓                | X                    | ✓                     |                |                     |
|          | HP and/or conventional systems                        | ✓                  | ✓                 |                        | ✓                 | ✓                  | ✓                        | ✓              | ✓                      | ✓              | ✓                | ✓                    | ✓                     |                |                     |
|          | distribution system (e.g. ADV)                        | X                  |                   |                        | ✓                 | X                  | ✓                        | ✓              | X                      | ✓              | ✓                | X                    | ✓                     |                |                     |
|          | operating cost components                             |                    |                   |                        |                   |                    |                          |                |                        |                |                  |                      |                       |                |                     |
|          | maintenance costs                                     | X                  |                   | ✓                      | ✓                 |                    | X                        | ✓              | ✓                      | ✓              | ✓                | X                    |                       | ✓              | ✓                   |
|          | HP and/or conventional systems el. en. use            | ✓                  | ✓                 | ✓                      | ✓                 | ✓                  | ✓                        | ✓              | ✓                      | ✓              | ✓                | ✓                    |                       | ✓              |                     |
|          | auxiliary el. en. use - heat source/sink side         | ✓                  |                   | ✓                      | ✓                 |                    |                          | ✓              |                        |                | ✓                | X                    |                       | X              |                     |
|          | auxiliary el. en. use - demand side                   | X                  |                   | ✓                      | ✓                 |                    |                          | ✓              |                        |                | ✓                | X                    |                       | X              |                     |

### 3.1 Identify and technically specify the different solutions to be assessed (STEP I)

Technically specify the solutions to be assessed means to assign performance to the buildings and to the technical heating and cooling systems compared. In the case of HPs this can be a very delicate step since performance depends on climatic as well as operating conditions.

Some studies simply assign an average coefficient of performance COP which defines the efficiency of the HP as constant during the years (Self et al. [12], Healy & Ugursal [18], Chiasson [25], see

Table 3). This approach is the least accurate because it does not take into account of any possible climatic or location-related variation which can affect the efficiency of the HP. In Figure 3 it can be noticed that the results of Self et al. [12] give a very optimistic life-cycle economic evaluation for HP systems compared to the conventional systems; this is also due to the fact that a constant value is assigned for defining HPs efficiencies. Most of the early studies adopt this approach.

**A more accurate approach to simulate performance of HPs is based on empirical curve-fit models derived from HP-manufacturer specifications** (e.g. Aste et al. [5], see

Table 3) **since they replicate the COP of the HP more precisely.**

Current advances in HP-simulation tools allow for improvements in life-cycle studies but they can also lead to very complicated simulations so, often, it is more practical to use polynomial curves.

In the case of GHPs, performance depends on ground temperatures; therefore, **thermal analysis of the ground heat exchanger (GHEX) based on updated simulation models is necessary in order to determine the temperature of the circulating heat-transfer fluid flowing into the HP.** The heat transfer process outside the borehole and the one in the region inside it (including grout, pipes and circulating fluid) are usually simulated separately. Heat transfer models of the GHEX are reported in the review of Yang [25].

Finally it is also important to define location and characteristics of the building where the technical systems are installed. Location and characteristics of the building determine the building thermal loads which influence the consumption of the HPs. **Dynamically simulating the building energy system allows calculating in an accurate way the building loads and this affects positively the reliability of the analysis.**

### ***3.2 Specify the main economic parameters to be used (STEP II)***

Specify the main economic parameters means to find the best way for defining escalation rates, discount rates and project lifespans.

**In the case of escalation rates (rates of annual increase of fuel and electricity costs), a possible approach is to consider time-series data describing the evolution of energy tariffs and to determine the rates based on statistical analysis of these data** (Aste et al. [5], see

Table 3). Some early studies (Healy & Ugursal [18], see

Table 3) have assumed constant prices of electricity and fuel, which is an unrealistic simplification.

Regarding the discounting of future costs, different interest rates are considered in the different works, the range is quite large. If the discount rate is chosen equal to zero it means that time has no impact on the costs, which is not recommended [24].

Finally, **a critical parameter (which can largely influence the LCC results) is the expected project lifetime**; a too short lifespan will favour the option with lower investment costs i.e. the conventional one. **The most used value is 20 years. To adopt a shorter lifetime than 20 years** (e.g. Aste et al. [5], see

Table 3) **appears pessimistic for HPs since many HP systems have been in operation for 25-30 years with no special maintenance** [15] [9]. Moreover, ground heat exchangers (GHEXs) in the case of GHPs have now a long predicted lifetime (over 30 years in the case of copper coils and over 50 years for polyethylene pipes with almost no maintenance needed [15]). In Figure 3 results of Aste et al. [5] are very pessimistic for HPs performance also because a lifespan of 15 years is chosen for the economic analysis.

**An advanced approach followed by Chiasson [31] is to use a very long lifespan (50 years) and to consider refurbishment costs for replacement of the less-lasting parts of the systems (e.g. pumps, outdoor parts, heat exchangers).**

### ***3.3 Determining the cost components (STEP III)***

An essential step in a LCC study is the definition of the costs. **Accuracy is important not only in the moment of acquiring cost data but, also, in the process of defining which costs are to be included in the evaluation.** Acquiring up-to-date cost data directly from local contractors and manufacturers is the best option, even though it could be the most complicated one.

In the case of HP systems four components can be distinguished for the calculation of the capital cost:

- cost of the environmental heat source/sink system (e.g. piping, pumps, fans);
- civil labour/installation costs (e.g. drilling, excavation);
- cost of the HP;
- cost of the distribution system (e.g. ADV, piping, pumps).

These four main categories represent a simplification of the problem but can help avoiding mistakes; for example, excluding the distribution costs in the comparison with a conventional boiler can bring to inaccurate final results since a low-temperature system (installed to enhance HP performance) is generally more expensive than ordinary radiators.

**Clearly specifying the cost-boundaries of the analysis (i.e. defining which costs are included and what is excluded) is a fundamental step to be undertaken (independently from the scope of the research) since it helps in understanding the results and makes them robust.** Some studies (Alavy et al. [34], Aste et al. [5], Self et al. [12], Kaygusuz [26], Tassou et al. [27], see

Table 3) are not accurate enough in defining the costs and, of course, this brings to uncertainties in the evaluation of the outcomes.

Operating costs include:

- maintenance and equipment-replacement costs;
- electrical energy consumption of the HP;
- electrical energy consumption of auxiliary equipment for heat-transfer fluid circulation (fans, pumps, etc.).

Maintenance and equipment-replacement costs are not always included, also due to difficulty of their estimation. Regarding the auxiliary electrical energy use, there are two main components:

- the electrical energy use in the heat source/sink side;
- the electrical energy consumption of pumps in the distribution side.

**Auxiliary consumption of the heat source/sink system is often included, but most studies do not consider the electrical consumption of the distribution system, most of the studies do not consider it. This is often inaccurate since pumps have a large share of the total consumption of the system [5] [6] and therefore they largely affect the operating costs.**

### ***3.4 Define a sensitive analysis (STEP IV)***

Sensitive analyses mainly focus on variations of energy tariffs and escalation rates since these are the most difficult values to estimate. This is also due to the fact that, in an economical life-cycle study, the cost of energy (electricity, natural gas, oil, coal) is a dominant factor influencing the NPV calculations.

## **4. Factors influencing economic and environmental performance for heat pumps**

While reviewing the various LCC studies it emerged that the economic life-cycle success of HPs depends on a number of different factors related both to the methodological assumptions (already discussed in Section 3) and to location and design aspects. The location and design aspects are treated in this chapter.

In the case of HP systems economic performance is closely related to the environmental one; therefore some factors influence both the economic and the environmental success of HPs and many factors are highly correlated among each other since a low efficiency of the HP affects negatively both the operating costs and the GHG emissions.

This work has until now focused only on the review of LCC analyses, in this section environmental performance is also taken into consideration in order to give a complete overview of factors influencing the overall sustainability of HPs; nevertheless LCA studies are not reviewed.

The factors identified in this study by reviewing LCC analyses are listed in Table 4 and further described in the following sections. Possible solutions and improvements are also given for each factor in the next sections. In Table 4 it is specified for each factor whether economic or environmental effects are involved. Furthermore it is pointed out whether it is a location or a design factor. The first ones depend on the conditions characterizing the location where the HP is installed, while the second ones depend on aspects related to the design of the system. The various types of HPs (ASHPs, SWHPs, GWHPs and GCHPs) are affected to a different extent by these factors as showed in Table 4.

Table 4 Factors influencing life-cycle performance of HP systems. A cross means that there is not any influence.

|   | LOCATION FACTOR | SYSTEM-DESIGN FACTOR | influencing:         |                           | affecting: |       |       |       |
|---|-----------------|----------------------|----------------------|---------------------------|------------|-------|-------|-------|
|   |                 |                      | ECONOMIC PERFORMANCE | ENVIRONMENTAL PERFORMANCE | ASHPs      | SWHPs | GWHPs | GCHPs |
| net energy balance of the thermal loads             | ✓               | ✓                    | ✓                    | ✓                         | x          | x     | ✓     | ✓     |
| capacity of the heat pump system                    | ✓               | ✓                    | ✓                    | ✓                         | ✓          | ✓     | ✓     | ✓     |
| design of the environmental heat source/sink system | x               | ✓                    | ✓                    | ✓                         | x          | ✓     | ✓     | ✓     |
| ground characteristics                              | ✓               | x                    | ✓                    | ✓                         | x          | x     | ✓     | ✓     |
| energy price ratio                                  | ✓               | x                    | ✓                    | x                         | ✓          | ✓     | ✓     | ✓     |
| climatic conditions                                 | ✓               | x                    | ✓                    | ✓                         | ✓          | ✓     | ✓     | ✓     |
| building design                                     | x               | ✓                    | ✓                    | ✓                         | ✓          | ✓     | ✓     | ✓     |
| size of the system                                  | x               | ✓                    | ✓                    | ✓                         | ✓          | ✓     | ✓     | ✓     |
| design and control of pumps                         | x               | ✓                    | ✓                    | ✓                         | ✓          | ✓     | ✓     | ✓     |
| capital costs                                       | ✓               | x                    | ✓                    | x                         | ✓          | ✓     | ✓     | ✓     |
| storage   | x               | ✓                    | ✓                    | ✓                         | ✓          | ✓     | ✓     | ✓     |
| technical performance of the HP and reliability     | x               | ✓                    | ✓                    | ✓                         | ✓          | ✓     | ✓     | ✓     |
| CO2 emission factors                                | ✓               | x                    | x                    | ✓                         | ✓          | ✓     | ✓     | ✓     |
| solar integration                                   | ✓               | ✓                    | ✓                    | ✓                         | ✓          | ✓     | ✓     | ✓     |

air-source heat pump (ASHP), surface water HP (SWHP), ground-water heat pump (GWHP), ground-coupled heat pump (GCHP)

#### 4.1 Net energy balance of the thermal loads

The evolution of the heating and cooling loads over the year affects the performance of geothermal heat pump (GHP) systems. In an unbalanced scenario, heating and cooling loads do not balance each other during the year and therefore there is a prevalence of one load respect to the other. **A yearly unbalanced load compromises the regeneration capacity of the ground and leads to unfavourable temperatures of the heat source/sink, this lowers the efficiency of the HP with consequent degradation of the environmental and economic performance** [12]. To maintain high efficiencies, the ground heat exchanger (GHEX) needs to have a larger size compared to the case of a balance load and, therefore, a higher initial cost. The study of Robert and Gosselin [11] compares the impact of two types of loads on the performance of a GHP; a constant only-heating load is compared with a transient heating and cooling load over the year. Total and

operating costs are higher for the only-heating load since the absence of the cooling load means that there is little thermal regeneration in the ground.

Furthermore, the requirement of both heating and cooling conditioning makes it possible for the HP to work in a reversible way avoiding the additional cost of a separate AC (air-to-air split conditioning unit) for space cooling; this leads to an extra economical advantage over the conventional systems [24] [12].

**The presence of a particularly unbalanced yearly distribution of the thermal loads can be solved with the use of a hybrid system;** for example, in the case of prevalence of the cooling load respect to the heating one, a fluid cooler (i.e. a cooling tower) can be added for helping the geothermal heat sink in the assimilation of the cooling loads. This has been found to be the option with the lowest life-cycle cost in the analyses of Bernier [20] and Yavuzturk [35]. Also in the study of Man [36] it is found that, for hot-weather only-cooling areas, the hybrid geothermal solution with cooling tower is largely more economical than the univalent one; total cost-savings of 53.59 % can be achieved in 10 years. Another study of Man [37] shows the economic feasibility of a geothermal heat pump combined with a nocturnal cooling radiator which is activated under ideal meteorological conditions. In the case of a dominant heating load a conventional boiler can meet a portion of the load in order to reduce the thermal stress on the ground. The cost effectiveness of a hybrid system depends on the size of the installation; small installations could not justify the use of bivalent systems.

**Using the HP for domestic hot water (DHW) production is another option for balancing the loads in cooling dominated climates;** for example the superheated gas from the compressor can be used in summer for partially heating DHW by means of a desuperheater (a special heat exchanger installed between the compressor and the condenser) and, in winter, more heat can be extracted from the ground for hot water production [31].

## **4.2 Capacity of the heat pump system**

Building peak loads occur only occasionally, the rest of the time being the technical system over-dimensioned. Furthermore, building loads are often over-estimated especially in very warm/cold climates [6]. In the case of ground-coupled heat pumps (GCHPs), sizing the HP system based on the peak loads can lead to very high initial investment costs due to the increased total length of the GHEX. **The use of a hybrid system allows reducing the peak ground loads and can therefore result in higher economic savings compared to a univalent system.** Performing a 20 years LCC analysis, Hackel [6] found that the hybrid system is the most economical solution compared to the univalent and conventional ones.

In a hybrid or bivalent system, the GCHP can run in parallel with an auxiliary system during peak loads so that the latter is only used to supply the additional peak heating requirement. In other configurations HP and auxiliary unit never run in parallel and the control system regulates the functioning of the system based on external parameters like the wet-bulb air temperature; in this case the auxiliary system is to be sized for the full peak load [36]. In the case of air-source heat pumps (ASHPs) the presence of an auxiliary system prevents the HPs to run at low efficiencies during unsuitable ambient temperatures.

**In order to be economic advantageous a bivalent system needs to be correctly sized based on a cost-minimization approach; simply sizing the HP capacity based**

**on the base heating load does not mean to reach the optimum cost since this strategy does not consider the energy exchange with the ground.** Sizing the equipment based on a LCC analysis approach makes it possible to realize the most life-cycle savings [6]. The study of Alavy [23] proposes a well-structured method for determining optimal-sized bivalent system based on a life-cycle cost optimization method. In the study of Dickinson, the optimum sized bivalent system ensures a reduction > 60 % in the capital cost compared to a peak sized GSHP system and, at the same time, still guarantees > 70 % of the economic savings and CO2 reduction [24].

#### **4.3 Design of the environmental heat source/sink system**

Increasing the total piping length of the GHEX favours the inlet temperature to the HP which becomes closer to the undisturbed ground temperature and therefore helps maintaining the efficiency of the HP at high levels and assures energy savings compared to conventional systems. On the other hand, it increases the initial costs of the GHEX which is one of the main factors preventing the adoption of GCHPs.

**Most of the methods currently used for designing and sizing GHEXs are based on 'rules of thumbs' or 'worst case scenario-calculations' and do not guarantee the most economical solution [11]. A correct designing and sizing of the GHEX based on total cost minimization (life-cycle optimization) is therefore a fundamental step for ensuring economic and environmental feasibility of the HP [20].** Already in 1997 the work of Healy and Ugursal [18] suggested the importance of carrying out a pre-design analysis in order to determine optimal parameters for the GHEX. A new method based on minimization of the costs has been proposed for vertical boreholes by Robert and Gosselin [11].

#### **4.4 Ground characteristics**

When designing a GCHP system, ground conditions (such as ground temperature, thermal conductivity of the soil/rock formation, ground water level) need to be well known since they influence the performance of the GHEX. As the ground thermal conductivity increases there is a reduction of the length of the boreholes due to the larger heat transfer per unit of length and, as consequences, operating costs (pumping costs) and also investment costs (especially drilling costs but also piping costs) decrease [16], the efficiency of the HP improves and the overall economic and environmental feasibility of the HP increases. **Knowing the ground conductivity is therefore important in the process of dimensioning the GHEX;** however, in order to know the exact value it is necessary to perform a thermal response test (TRT) which is quite expensive.

In the study of Robert and Gosselin [11] it is found that, **for the case of small borefields, it is more convenient to use an approximate value for the ground conductivity than to perform a TRT.** Pulat [29] also suggests that a reliable estimate of thermal conductivity of the soil is more important than carrying out extensive measurements.



#### 4.5 Energy price ratio

The actual energy price ratio and its evolution in time due to escalation of electricity and heating fuel prices are the most important factors affecting the competitiveness of HP systems. **Currently, in most of the world, only natural gas-driven boilers or furnaces are able to compete with HPs [22]. However, when the cost of natural gas is low compared to electricity HPs are likely not to be the most competitive option [12].**

#### 4.6 Climatic conditions

Climatic conditions affect the inlet fluid temperatures to the HPs and therefore influence the performance of HP systems. A decrease in the outdoor temperature lowers the heating capacity and the COP of ASHPs. A high outdoor humidity also plays a major role in defining the efficiency of ASHPs since it increases the frequency of defrost cycles. Ambient temperature and solar irradiation can affect efficiency in the case of GHPs using horizontal collectors.

#### 4.7 Building design

The environmental and economic success of a HP system depends on the characteristics of the building where the HP is installed (i.e. thermal quality of the envelope, air tightness of the building, temperature of the distribution system, etc.). **As the building becomes more energy efficient and the heating/cooling loads reduce, the GHP system becomes a better option since size and initial costs of the GHEX can be reduced as well [7]. However, economic performance of ASHPs is not influenced by the size of the building loads.** Marszal and Heiselberg [39] compared the life-cycle costs of ASHPs and GHPs installed together with photovoltaic panels (PV) and photovoltaic/solar thermal installations (PV/T) in net ZEBs having 3 different levels of energy demand; they found that the GHP installed in the highest energy-efficient building (i.e. with the lowest energy demand) is the cost-optimal case. Energy efficient measures combined with HPs are therefore crucial for realizing a cost-optimized net ZEB.

**In the case of retrofitting existing building** (which is the most common situation) it is found that solutions only based on increasing performance of the building envelope are not cost-optimal since high performance envelopes are very expensive; **implementing high-efficient HPs is the most cost-effective option for realizing savings in the energy consumption [40].**

**It is also very important to correctly size the building loads in order to not overestimate the required HP-capacity.**

Another main design factor which needs to be considered is the temperature of the distribution system. Good thermal insulation and enhanced air tightness make it possible to use distribution systems with temperatures lower than 50°C [41]. **Low-temperature water distribution systems are found to be the most effective for enhancing performance of HPs since they reduce the temperature lift (i.e. the difference between heat sink/source and load temperatures) across the HP.**

## 4.8 Size of the system

Small installations include solutions like single-house systems, while among the largest installations there are, for example, applications in big residential complexes or commercial applications. **Large-size applications are the ones often showing the most of the advantages in terms of economic and environmental performance [22] since capital costs can benefit from economies of scales and larger loads make operating savings more valuable [22].** Alavy [34] studies the cost-effectiveness of the integration of various buildings using a common water loop and a hybrid GCHP and compares it with the case of a single hybrid GCHP installed in each building. It is found that integrating cooling and heating dominant buildings with a common water loop and heat pump is the most effective solution since the heating and cooling loads can partially compensate each other's and this allows to reduce the capacity of the hybrid heat pump with consequent reduction of the capital costs.

## 4.9 Design and control of pumps

The electrical energy use of the auxiliary equipment (pumps, fans, etc.) has a non-negligible impact on the efficiency performance of HP systems. In the study of Aste [5] auxiliary energy consumption is in the range of 4-6 % for ASHPs and 18-22 % for GWHPs of the total primary energy use. Hackel and Pertzborn measured that pumping contributes between the 7 % and 21 % to the total electrical consumption for GCHP systems [6]. Therefore a good design and control of pumps is essential for reducing auxiliary consumption and assuring economic and environmental feasibility of HPs.

An HP-system works most of the time at part load, thus for maintaining high performance is important:

- not to oversize pumps because this leads to very low part-load efficiencies;
- to select and control variable-speed pumps in order to significantly reduce their speed at part load.

**Correct sizing and part load control of pumps are primary aspects to be taken into account for a correct design of a HP-system [6].**

Other general factors for achieving an efficient pumping operation are:

- in order to avoid to run the pumps uselessly, to make them to switch off when fluid temperatures are in a 'dead-range';
- to use larger piping;
- to diminish valving and connections;
- to minimize antifreeze.

In the study of Hackel and Pertzborn [6] it has been found that with the above part load improvements a reduction of 40 % of the pumping energy per year can be achieved.

## 4.10 Capital costs

**Capital costs have a big influence on the life-cycle total cost of HPs.** Capital costs of HP systems depend on the market uptake of the technology as well as on the presence of subsidy-schemes and specific economic trends. Since subsidies vary in the different

countries (in some regions HPs are not subsidized at all) and market conditions change regionally based on how much the market is developed and on local factors (e.g. labour rates, geological conditions, etc.), capital costs depend on location. In the analysis of Blum [42] it is found that, for the installation of small-scale vertical GSHP, the subsurface conditions of the site do not define the capital costs but only market dynamics are decisive.

**Capital costs are expected to lower in the future thanks to the increased implementation of HPs and consequent learning curves effects [22] [14]. Besides this, policy initiatives will play an essential role for reducing initial costs and helping end-users to encounter the investments.**

#### ***4.11 Storage***

A water tank for thermal storage in combination with a HP can substitute hybrid systems in small-capacity applications helping in the management of peak loads; it can also help in avoiding an excessive on-off cycling of the heat pump in part-load conditions. The presence of storage in the building design, when correctly implemented and controlled, can therefore make a difference in the life-cycle economic success of a HP-system.

#### ***4.12 Technical performance of the HP and reliability***

The technical performance of HPs has evolved in the last decades thanks to improvement and optimization of system components. The adoption of these improvements influences in a positive way the economic and environmental feasibility of HPs. The main improvements are:

- invention and adoption of scroll compressors presenting an isentropic efficiency about 10 % higher than that of reciprocating compressors;
- invention and adoption of electronic expansion valves in place of mechanical ones;
- improvements in heat exchangers design (implementation of micro-channel heat exchangers having large surfaces which enhance heat transfer);
- implementation of capacity modulating HPs (thanks to the introduction of variable/modulating speed compressors such as inverter compressors, digital scroll compressors and multiple compressors) with consequent favourable reduction of the number of compressor starts in part-load conditions [7].

Furthermore, various commercially available solutions aim to enhance the technical efficiency of HPs with respect to the working conditions (temperatures and loads). Among them, there are multistage compound systems and cascade systems [30]. The firsts consist of more than one compressor stages connected in series, while the seconds are constituted by two single stage systems which operate in an independent manner but are connected by a cascade condenser. Both systems are designed for higher temperature lifts, for example for DHW production or in industrial applications.

#### 4.13 CO<sub>2</sub> emission factors

Regarding the environmental impacts associated with the use of HPs, it is possible to distinguish between direct and indirect effects. Direct effects are those related with the global warming potential (GWP) of the F-gases released in the case of accidental leakage. While indirect effects are provoked by the emissions associated with electricity-production. Indirect effects are usually more serious than the direct ones [20] [44].

Among the indirect emissions, CO<sub>2</sub> emissions are to be primarily taken into account since CO<sub>2</sub> is the most common GHG and is considered the main contributor to climate change [45]. Therefore, environmental impacts of HPs depend on the CO<sub>2</sub> emission factors of the region where the electricity used by the HP is produced. **Locations where electricity is mainly produced by nuclear, hydroelectric or other renewable power plants have lower CO<sub>2</sub> emission factors than regions relying on thermal fossil-fuel power plants; therefore, in these locations characterized by low carbon emissions HP-systems can be an environmental successful alternative** [12]. In accordance with the analysis of Hanova & Dowlatabadi [45], if the regional emission intensity is less than 0.76 kg/kWh then a GHP system offers environmental advantages (i.e. emission reduction) compared to a natural gas furnace with an efficiency of 0.95. Higher efficient HPs are environmental advantageous even in regions with higher emission intensity.

#### 4.14 Solar integration

Solar thermal or photovoltaic (PV) systems can be combined with HPs in order to reduce the electricity consumption of HP systems. Solar integration into HP designs is of growing interest and, since there is still a lot to explore, the influence of this factor on the life-cycle environmental and economic success of HP systems can be large in the future. This is why it has been included in this overview.

There are different possibilities of using solar heat, e.g. domestic hot water heating, building heating, ground recharge, temperature increase in the evaporator; therefore the optimum configuration for the integration of solar collectors into HP systems is not easy to evaluate [46]. Moreover, advances in the control system have made it possible to realize different new configurations, but the complexity of these configurations causes more difficulties in finding optimum designs. According to Kjellsson [46], in the case of GCHPs if the system has a good design (i.e. good design of GHEX, HP capacity and pumps) and is well operated, **using solar collectors during summer for producing sanitary hot water and during winter for borehole-recharging is the best option from an energy point of view**. Chiasson & Yavuzturk [33] have performed a 20 years-life-cycle analysis showing that using solar collectors with GCHP is a viable option in heating-dominated climates.

The integration of PV and HP is particularly interesting because of the summer operation when the high electricity production of the PV meets the high cooling load required from the HP. According to the analysis of Thygesen and Karlsson [47], integration of PV and HP is an environmental and economic superior alternative compared to the integration with solar collector systems.

## 5. Conclusions

This work focuses on economic life-cycle analyses and presents a review of life-cycle cost studies involving electrically-driven HPs. The aim is to encourage and facilitate the adoption of LCC studies when considering heating and cooling solutions including HP systems. From the review of the LCC methodologies it is found that the most influential factors in achieving a reliable evaluation can be summarized as it follows:

- simulation of HP-performance based on empirical curve-fit models derived from HP-manufacturer specifications;
- thermal analysis of the GHEXs based on updated simulation models;
- dynamic simulation of the building energy system;
- determination of escalation rates based on statistical analysis of time-series data describing the evolution of energy tariffs;
- use of a long lifespan (50 years) with the consequent inclusion of costs for replacement of short-lasting parts of the systems (e.g. pumps, outdoor parts, heat exchangers);
- clear specification of the cost boundaries of the analysis;
- clear specification of which components of the auxiliary energy consumption are included.

The scope of this work is also to present an overview of factors influencing both the economic and the environmental success of HP systems. It is found that the most important factors to take into account for achieving good environmental and economic life-cycle performance are the following ones:

- A balanced yearly distribution of the thermal loads for GHPs. The problem of an unbalanced load can be solved with the use of a hybrid system (mostly a combination of HPs with gas/oil boilers or fluid coolers). Using the HP for domestic hot water production is another option for balancing the loads in cooling-dominated climates.
- Avoid sizing the HP system based on the peak loads for GHPs. The use of a hybrid system allows reducing the peak ground loads and the initial investment costs; it can therefore result in higher economic savings compared to a univalent system. In order to correctly size the hybrid system, a cost-minimization approach is to be followed; simply sizing the HP capacity based on the base heating load does not mean to reach the optimum cost.
- Designing and sizing the GHEX based on a total cost minimization (life-cycle optimization) approach. Most of the methods currently used for designing and sizing the GHEX are based on 'rules of thumbs' or 'worst case scenario-calculations' and do not guarantee the most economical solution.
- Knowing the ground conductivity in the process of dimensioning the GHEX. For the case of small borefields, it is more convenient to use an approximate value for the ground conductivity than to perform a thermal response test.

- Installing the GHP in an energy efficient building. In this way the heating/cooling loads reduce and therefore size and initial costs of the GHEX can be reduced as well.
- Correctly sizing the building loads in order to not mislead HP-capacity calculations.
- Using low-temperature water distribution systems because they reduce the temperature lift (i.e. the difference between heat sink/source and load temperatures) across the HP.
- Correctly sizing and part load controlling pumps since electrical energy use of the auxiliary equipment is a major part of the total electrical consumption of the system.
- Reducing initial costs with policy initiatives in order to help end-users to encounter the investments.

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### **Abstract**

Space heating and cooling together with sanitary hot water supply have a significant share, approximately 50 %, of the global energy consumption of buildings. In order to fulfil energy and energy-efficiency building requirements, European and national legislations encourage the use of more sustainable heating and cooling options. A sustainable dimension implies that both environmental and economic aspects are taken into account; the life-cycle comparisons of different heating and cooling systems are therefore based on GHG emissions and costs. This work focuses only on the economic side of the life-cycle analyses (therefore excluding the environmental dimension) and presents a review of life-cycle cost (LCC) studies involving HP systems. The first objective is to present an overview of the most influential factors characterizing life-cycle cost methodologies for HP systems and to suggest methodological improvements which can make LCC analyses more robust. The second objective is to present an overview of factors influencing both the economic and the environmental success of HP systems. A greater awareness and understanding of these factors can, at a macro-level, increase confidence in HP systems so that governments can identify appropriate actions and develop legislation that provide support for HPs implementation.

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